TOWARD AN EFFECTIVE FIELD THEORY FOR LHC JETS

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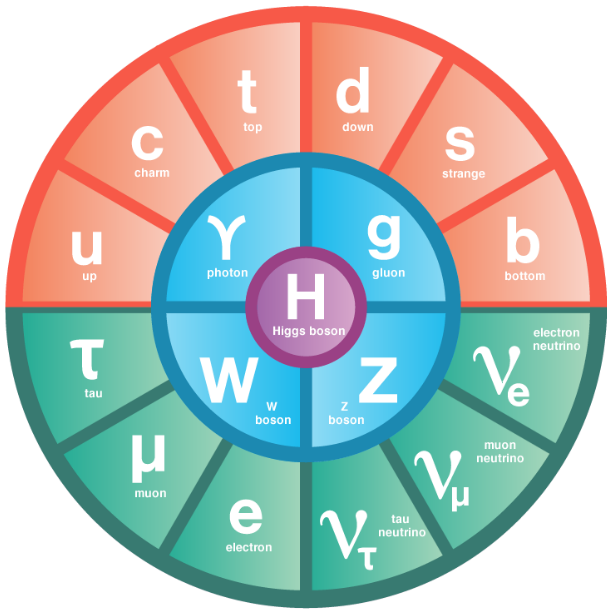
STANDARD MODEL TESTS AND NEW PHYSICS SEARCHES



symmetrymagazine.org

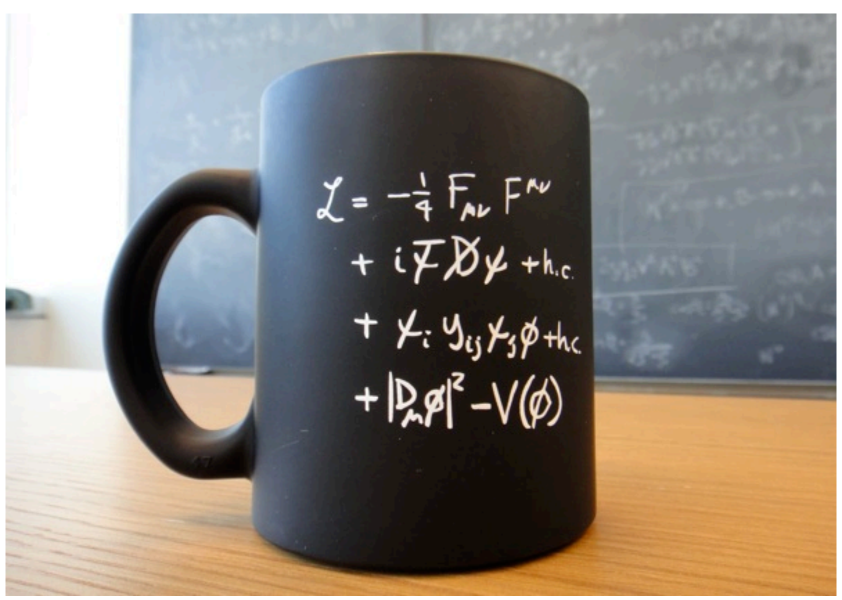


Photo by CERN

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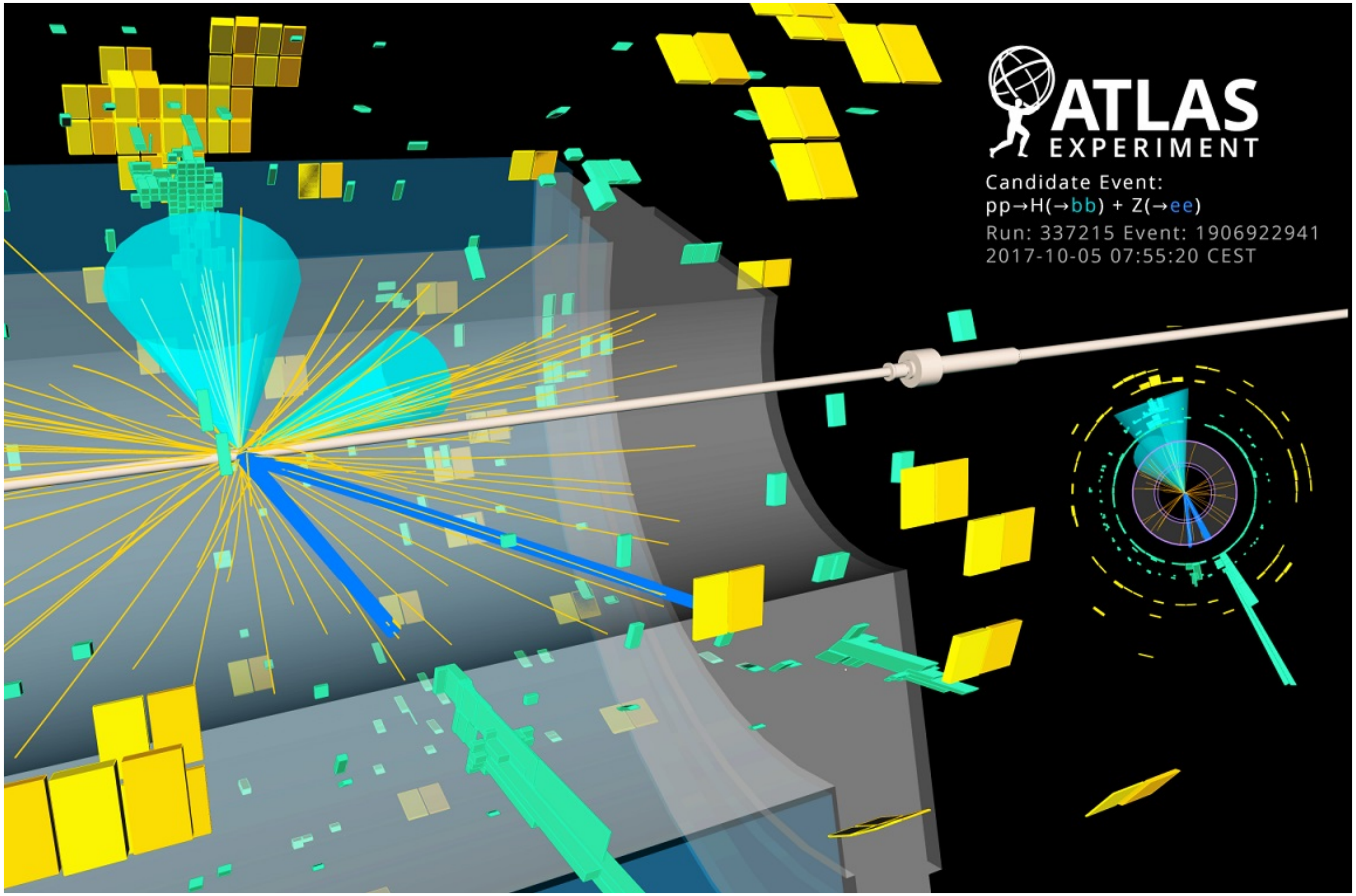
- Origin of Dark Matter?
- Abundance of matter over antimatter?

THEORY OF JET PROCESSES AT LHC



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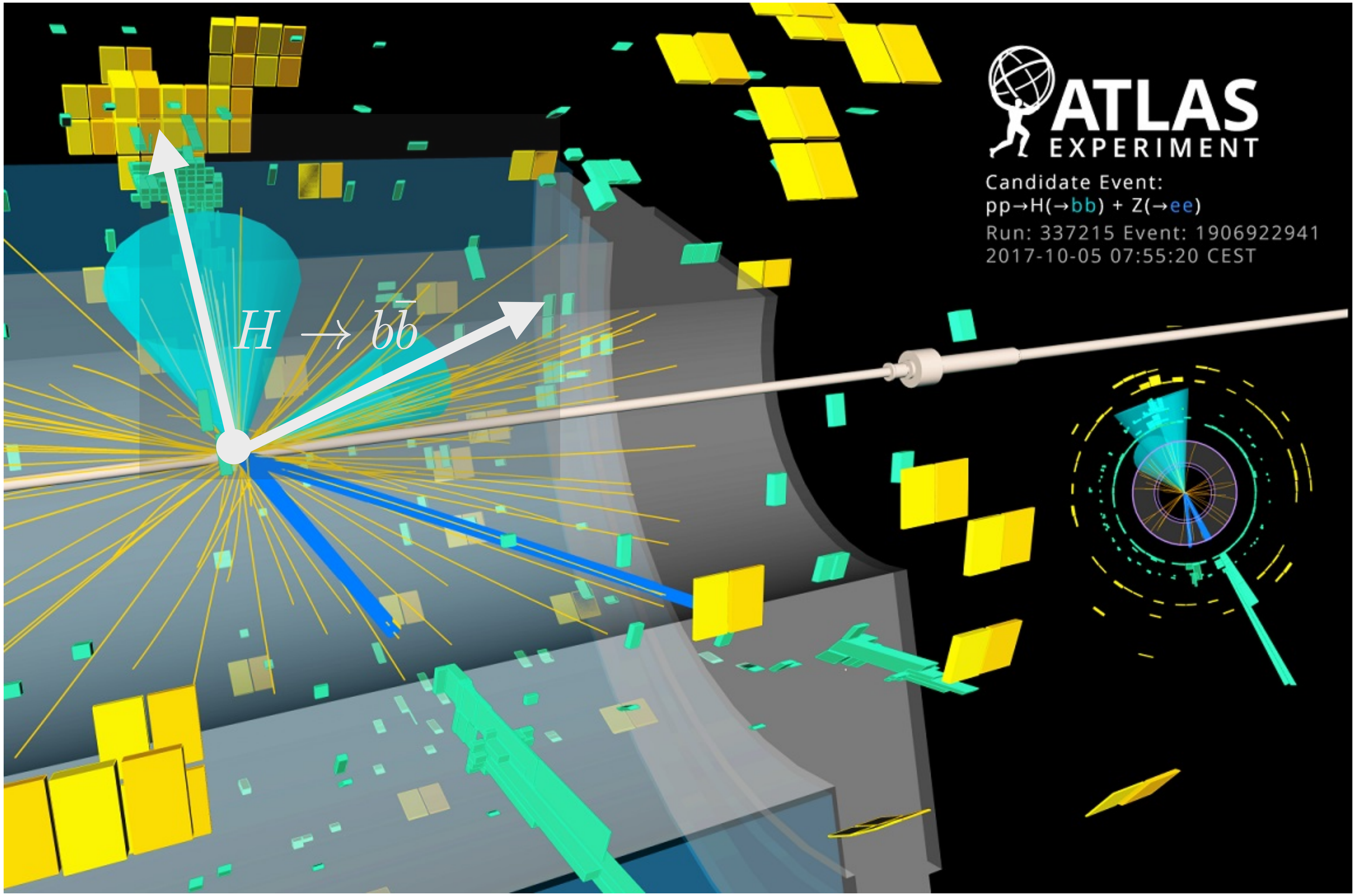

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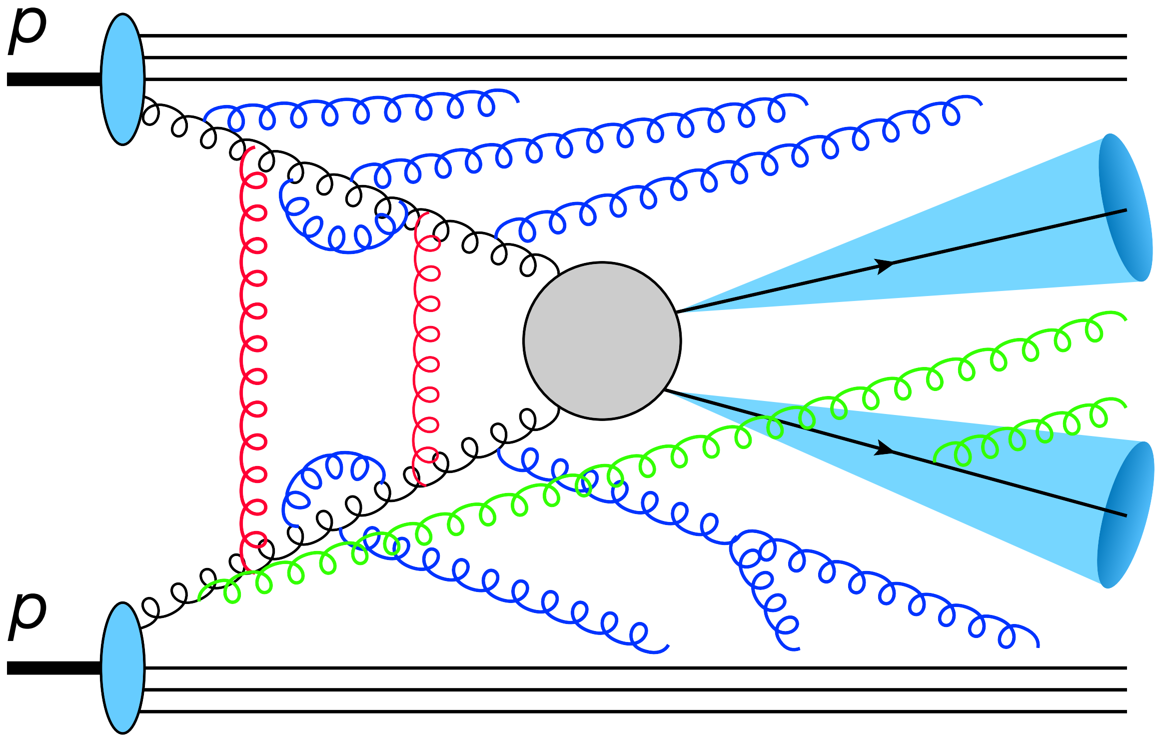

red: Coulomb gluons

blue: gluons emitted along beams

green: soft gluons between jets

[Forshaw, Kyrieleis, Seymour 2006]

Loss of color coherence from initial-state Coulomb interactions

$$d\sigma_{pp\to f}(s) = \sum_{a,b=q,\bar{q},g} \int dx_1 dx_2\, f_{a/p}(x_1,\mu)\, f_{b/p}(x_2,\mu)\, d\sigma_{ab\to f}(\hat{s}=x_1x_2s,\mu)$$

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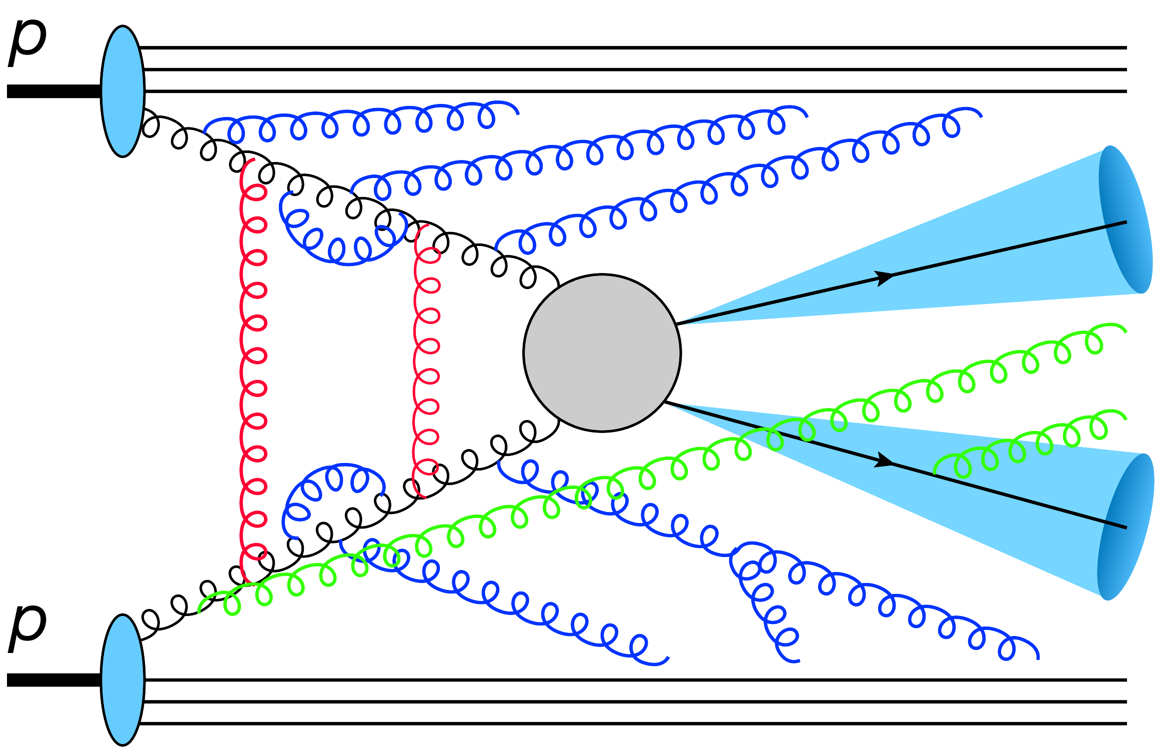

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Loss of color coherence from initial-state Coulomb interactions

- Weird "superleading logarithms"
- Breakdown of naive factorization
- Phenomenological consequences?

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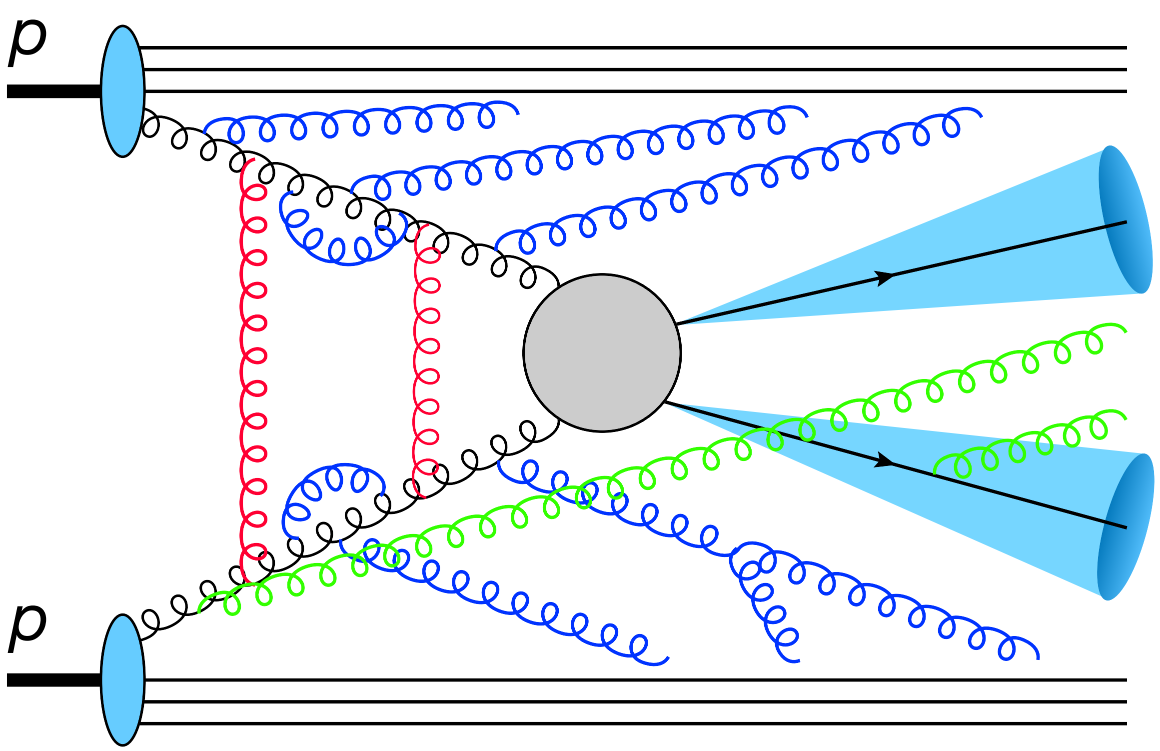

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Loss of color coherence from initial-state Coulomb interactions

- Weird "superleading logarithms"
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$$d\sigma_{pp\to f}(s) \neq \sum_{a,b=q,\bar{q},g} \int dx_1 dx_2\, f_{a/p}(x_1,\mu)\, f_{b/p}(x_2,\mu)\, d\sigma_{ab\to f}(\hat{s}=x_1 x_2 s,\mu)$$

SLLs

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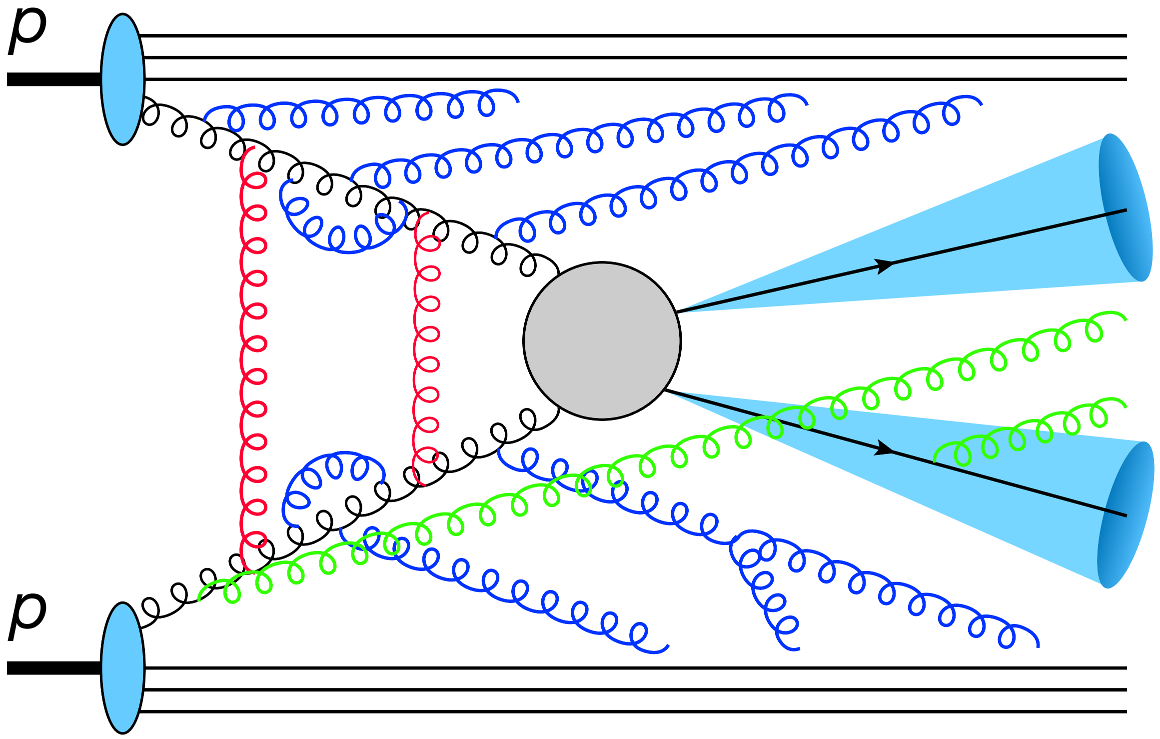

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Loss of color coherence from initial-state Coulomb interactions

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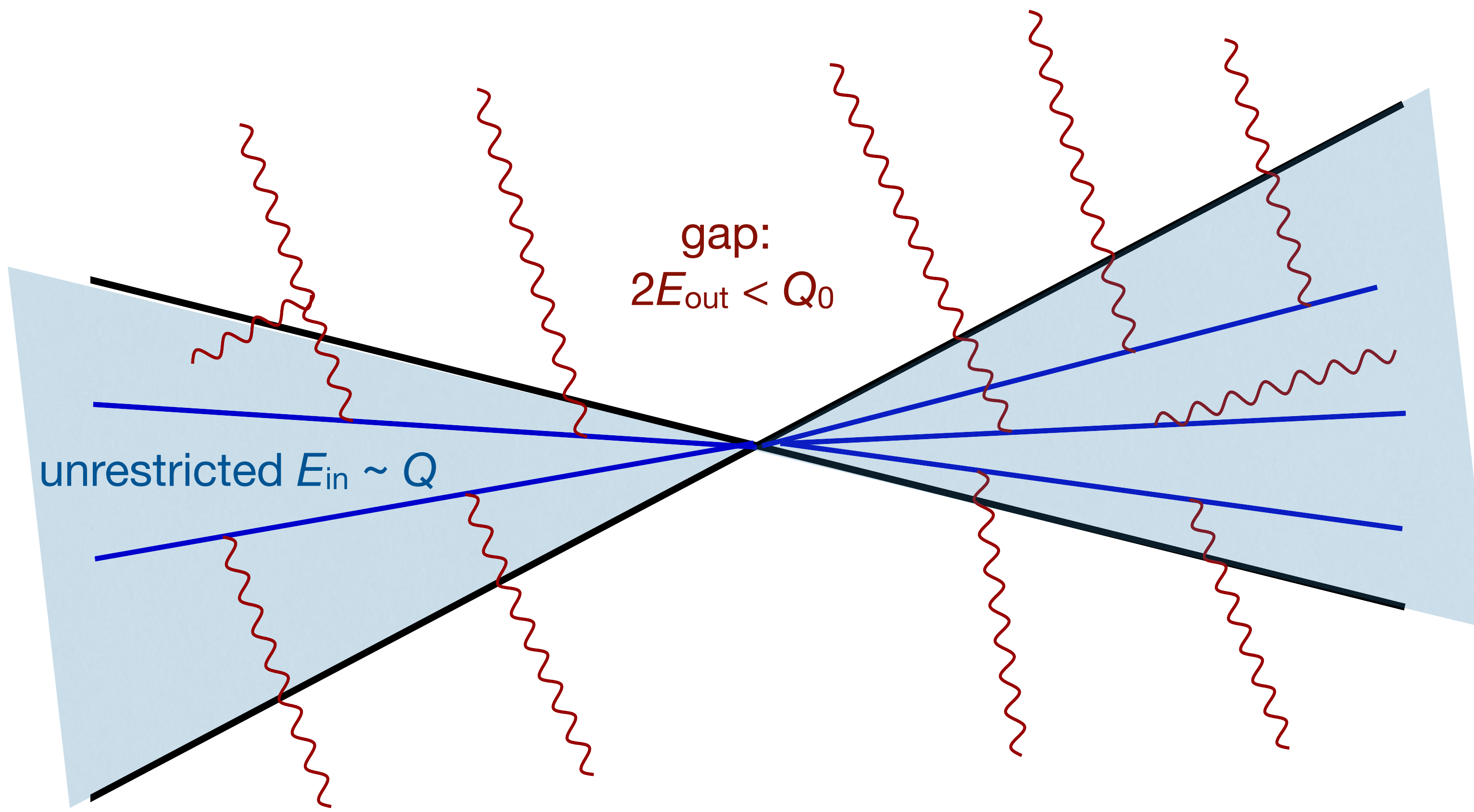
Need for a complete theory of quantum interference effects in jet processes!

THEORY OF JET PROCESSES AT LHC



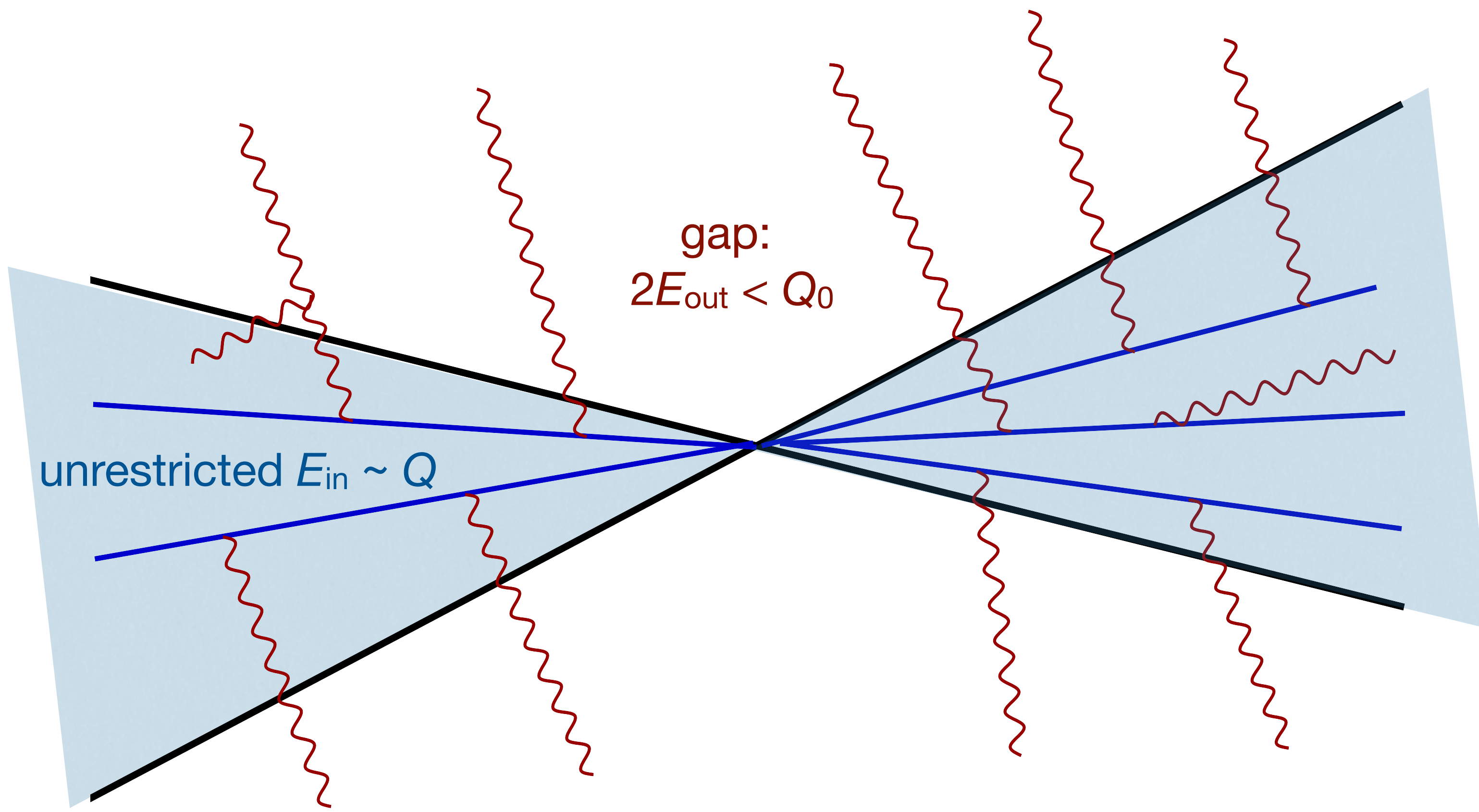
$$L = \ln(Q/Q_0) \gg 1$$

Perturbative expansion:

$$\sigma \sim \sigma_{\text{Born}} \times \{1 + \alpha_s L + \alpha_s^2 L^2\}$$

state-of-the-art: 2-loop order

THEORY OF JET PROCESSES AT LHC



$$L = \ln(Q/Q_0) \gg 1$$

Perturbative expansion including "superleading" logarithms:

$$\sigma \sim \sigma_{\rm Born} \times \Big\{ 1 + \alpha_s L + \alpha_s^2 L^2 + \alpha_s^3 L^3 + \underbrace{\alpha_s^4 \, L^5 + \alpha_s^5 \, L^7 + \dots}_{\sim (\alpha_s L)^3 (\alpha_s L^2)^n} \Big\}$$

$\sim (\alpha_s L)^3 \, (\alpha_s L^2)^n$: **formally larger than $O(1)$**

[Forshaw, Kyrieleis, Seymour 2006]

state-of-the-art: 2-loop order

THEORY OF JET PROCESSES AT LHC

Novel factorization theorem

$$\sigma_{2\to M}(Q,Q_0) = \sum_{a,b=q,\bar{q},g} \int dx_1 dx_2 \sum_{m=2+M}^{\infty} \big\langle \underbrace{\boldsymbol{\mathcal{H}}_m^{ab}(\{\underline{n}\},Q,\mu)}_{\text{high scale}} \otimes \underbrace{\boldsymbol{\mathcal{W}}_m^{ab}(\{\underline{n}\},Q_0,x_1,x_2,\mu)}_{\text{low scale}} \big\rangle$$

[Becher, MN, Shao 2021]

Renormalization-group equation:

$$\mu \frac{d}{d\mu} \boldsymbol{\mathcal{H}}_l^{ab}(\{\underline{n}\},Q,\mu) = -\sum_{m\le l} \boldsymbol{\mathcal{H}}_m^{ab}(\{\underline{n}\},Q,\mu)\, \boldsymbol{\Gamma}_{ml}^{H}(\{\underline{n}\},Q,\mu)$$

operator in color space and in the infinite space of parton multiplicities

$\Rightarrow$ new perspective to think about non-global observables

RESUMMATION OF SUPERLEADING LOGARITHMS

All-order summation of large logarithmic corrections, including the superleading logarithms:

$$d\sigma_{\mathrm{SLL}} = d\sigma_{\mathrm{Born}} \sum_{n=0}^{\infty} \left(\frac{\alpha_s}{4\pi}\right)^{n+3} L^{2n+3} \frac{(-4)^n\, n!}{(2n+3)!} \sum_{r=0}^{n} \frac{(2r)!}{4^r\,(r!)^2}\, C_{rn}$$

with color traces:

$$C_{rn} = -256\pi^2\,(4N_c)^{n-r} \left[\sum_{j=3}^{M+2} J_j \sum_{i=1}^{4} c_i^{(r)} \left\langle \boldsymbol{\mathcal{H}}_{2\to M}\, \boldsymbol{O}_i^{(j)} \right\rangle - J_{12} \sum_{i=1}^{6} d_i^{(r)} \left\langle \boldsymbol{\mathcal{H}}_{2\to M}\, \boldsymbol{S}_i \right\rangle \right]$$

[Becher, MN, Shao, Stillger (in preparation)]

kinematic factors (dependent on veto region)

RESUMMATION OF SUPERLEADING LOGARITHMS

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Basis of color structures:

$$\boldsymbol{O}_1^{(j)} = f_{abe}f_{cde}\,\boldsymbol{T}_2^a\,\{\boldsymbol{T}_1^b,\boldsymbol{T}_1^c\}\,\boldsymbol{T}_j^d - (1\leftrightarrow 2)$$

$$\boldsymbol{O}_2^{(j)} = d_{ade}d_{bce}\,\boldsymbol{T}_2^a\,\{\boldsymbol{T}_1^b,\boldsymbol{T}_1^c\}\,\boldsymbol{T}_j^d - (1\leftrightarrow 2)$$

$$\boldsymbol{O}_3^{(j)} = \boldsymbol{T}_2^a\,\{\boldsymbol{T}_1^a,\boldsymbol{T}_1^b\}\,\boldsymbol{T}_j^b - (1\leftrightarrow 2)$$

$$\boldsymbol{O}_4^{(j)} = 2C_1\,\boldsymbol{T}_2\cdot\boldsymbol{T}_j - 2C_2\,\boldsymbol{T}_1\cdot\boldsymbol{T}_j$$

$$\boldsymbol{S}_1 = f_{abe}f_{cde}\,\{\boldsymbol{T}_1^b,\boldsymbol{T}_1^c\}\,\{\boldsymbol{T}_2^a,\boldsymbol{T}_2^d\}$$

$$\boldsymbol{S}_2 = d_{ade}d_{bce}\,\{\boldsymbol{T}_1^b,\boldsymbol{T}_1^c\}\,\{\boldsymbol{T}_2^a,\boldsymbol{T}_2^d\}$$

$$\boldsymbol{S}_3 = d_{ade}d_{bce}\left[\boldsymbol{T}_2^a\left(\boldsymbol{T}_1^b\boldsymbol{T}_1^c\boldsymbol{T}_1^d\right)_+ + (1\leftrightarrow 2)\right]$$

$$\boldsymbol{S}_4 = \{\boldsymbol{T}_1^a,\boldsymbol{T}_1^b\}\,\{\boldsymbol{T}_2^a,\boldsymbol{T}_2^b\}$$

$$\boldsymbol{S}_5 = \boldsymbol{T}_1\cdot\boldsymbol{T}_2$$

$$\boldsymbol{S}_6 = \boldsymbol{1}$$

RESUMMATION OF SUPERLEADING LOGARITHMS

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[Becher, MN, Shao, Stillger (in preparation)]

Coefficient functions:

$$c_1^{(r)} = 2^{r-1} \left[(3N_c+2)^r + (3N_c-2)^r \right]$$

$$c_2^{(r)} = 2^{r-2} N_c \left[\frac{(3N_c+2)^r}{N_c+2} + \frac{(3N_c-2)^r}{N_c-2} - \frac{(2N_c)^{r+1}}{N_c^2-4} \right]$$

$$c_3^{(r)} = 2^{r-1} \left[(3N_c+2)^r - (3N_c-2)^r \right]$$

$$c_4^{(r)} = 2^{r-1} \left[\frac{(3N_c+2)^r}{N_c+1} + \frac{(3N_c-2)^r}{N_c-1} - \frac{2N_c^{r+1}}{N_c^2-1} \right]$$

$$d_1^{(r)} = 2^{3r-1} \left[(N_c+1)^r + (N_c-1)^r \right] - 2^{r-1} \left[(3N_c+2)^r + (3N_c-2)^r \right]$$

$$d_2^{(r)} = 2^{3r-2} N_c \left[\frac{(N_c+1)^r}{N_c+2} + \frac{(N_c-1)^r}{N_c-2} \right] - 2^{r-2} N_c \left[\frac{(3N_c+2)^r}{N_c+2} + \frac{(3N_c-2)^r}{N_c-2} \right]$$

$$d_3^{(r)} = 2^{r-1} N_c \left[\frac{(3N_c+2)^r}{N_c+2} + \frac{(3N_c-2)^r}{N_c-2} - \frac{(2N_c)^{r+1}}{N_c^2-4} \right]$$

$$d_4^{(r)} = 2^{3r-1} \left[(N_c+1)^r - (N_c-1)^r \right] - 2^{r-1} \left[(3N_c+2)^r - (3N_c-2)^r \right]$$

$$d_5^{(r)} = 2^r \,(C_1+C_2) \left[\frac{N_c+2}{N_c+1} (3N_c+2)^r - \frac{N_c-2}{N_c-1} (3N_c-2)^r - \frac{2N_c^{r+1}}{N_c^2-1} \right] - \frac{2^{r-1} N_c}{3} \left[(N_c+4)\,(3N_c+2)^r + (N_c-4)\,(3N_c-2)^r - (2N_c)^{r+1} \right]$$

$$d_6^{(r)} = 2^{3r+1} C_1 C_2 \left[(N_c+1)^{r-1} + (N_c-1)^{r-1} \right] (1-\delta_{r0}) - 2^{r+1} C_1 C_2 \left[\frac{(3N_c+2)^r}{N_c+1} + \frac{(3N_c-2)^r}{N_c-1} - \frac{2N_c^{r+1}}{N_c^2-1} \right]$$

RESUMMATION OF SUPERLEADING LOGARITHMS

All-order summation of large logarithmic corrections, including the superleading logarithms!

⇒ **Example:** Summation of superleading logarithms for $qq \to qq$ scattering in color-singlet channel:

$$\sigma_{\rm SLL} = -\sigma_{\rm Born} \boxed{\frac{16\alpha_s L}{81\pi} \Delta Y} \left(3\alpha_s L\right)^2 {}_2F_2\Big(1,1;2,\frac{5}{2};-w\Big) \sim \left(\alpha_s L\right)^3 \sum_{n\ge 0} c_n \left(\alpha_s L^2\right)^n$$

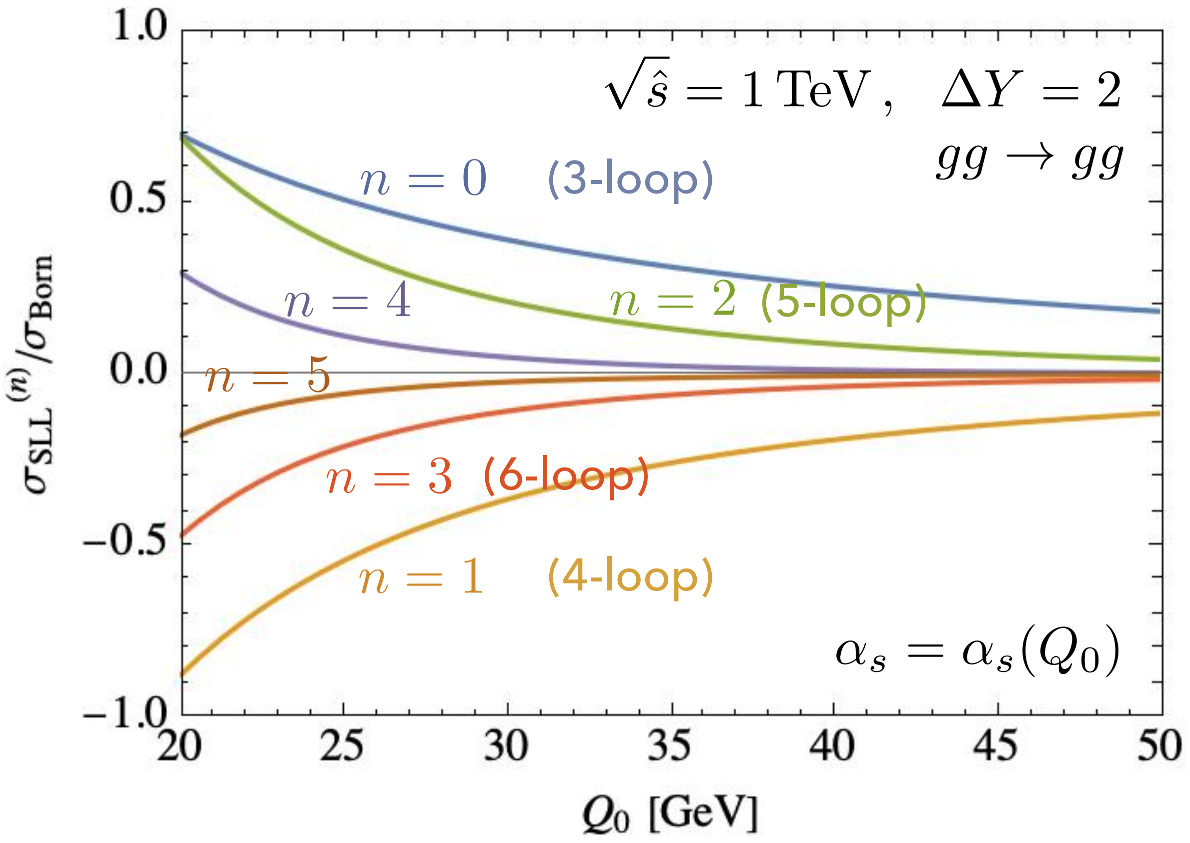
1-loop factor

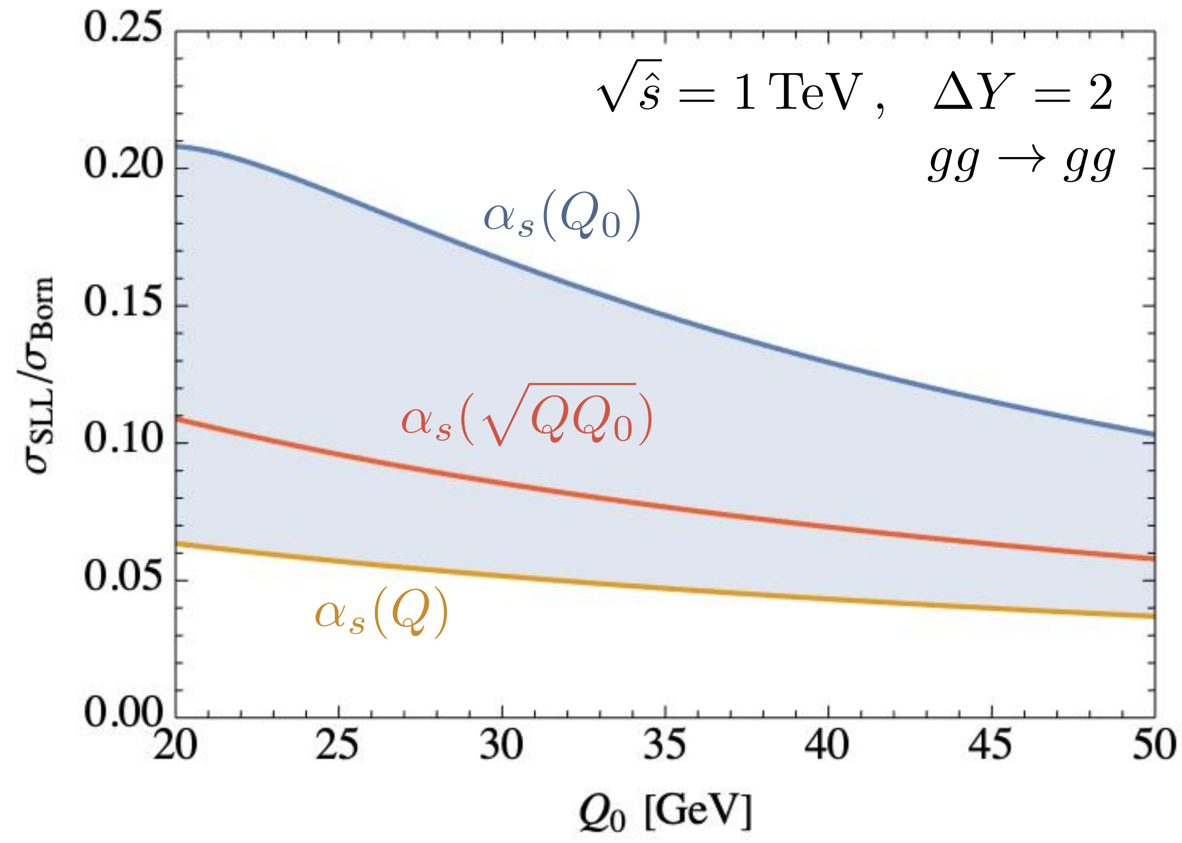
$$w = \frac{3\alpha_s}{\pi} L^2$$

[Becher, MN, Shao 2021]

RESUMMATION OF SUPERLEADING LOGARITHMS

Phenomenological impact in forward gluon-gluon scattering:





$\Rightarrow$ necessary to include eight terms (≤ 10 loops) to obtain reliable results; resummation formalism is essential!

EXPLORING UNCHARTERED TERRITORY

Important open questions

- Do the strong cancellations persist when subleading terms are included? How large is the remaining scale ambiguity?

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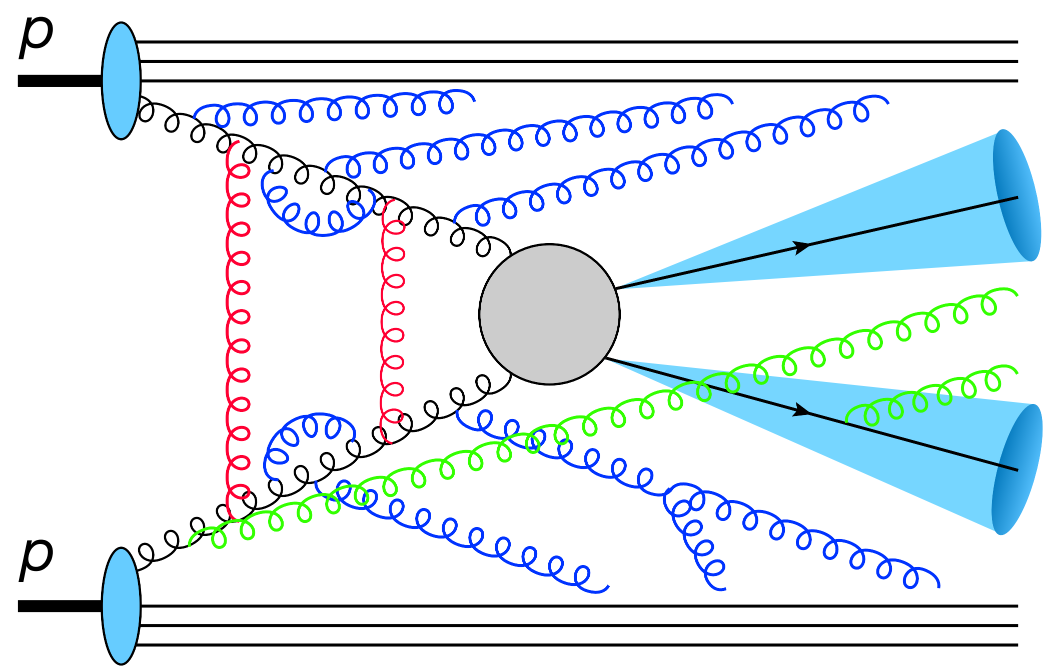
- Can factorization violations be understood in a quantitative way? Can a more general notion of factorization be established?



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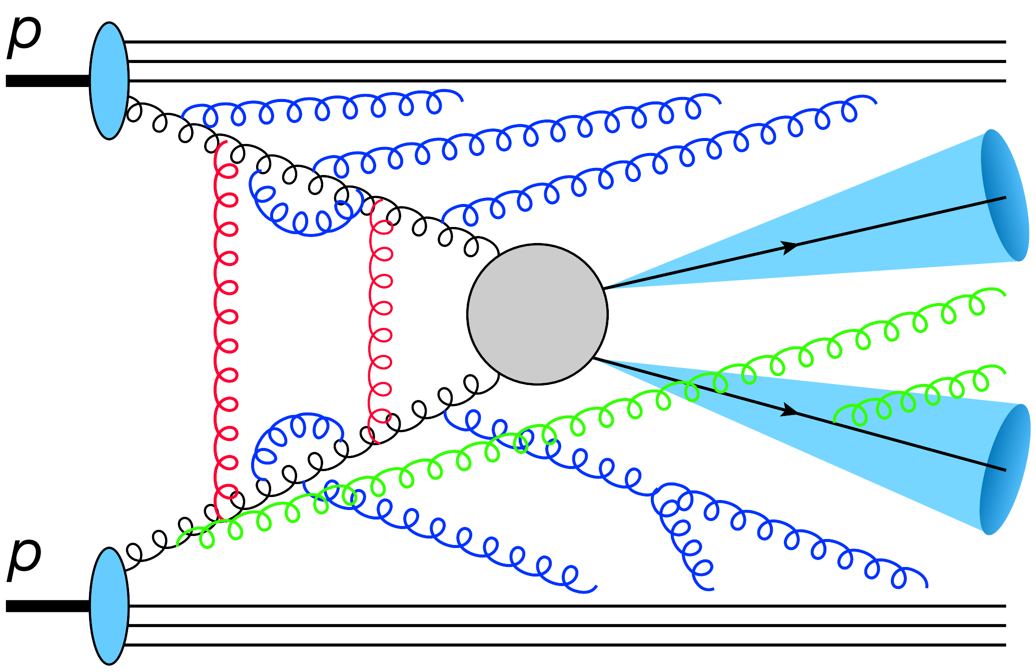
Important open questions

- Do the strong cancellations persist when subleading terms are included? How large is the remaining scale ambiguity?
- Can factorization violations be understood in a quantitative way? Can a more general notion of factorization be established?
- What are the implications for LHC phenomenology? Some benchmark processes: $pp \to 2\,\text{jets}$, $pp \to H/V + \text{jets}$, $pp \to \text{jet} + \not{E}_T$, $pp \to$ new particles, …



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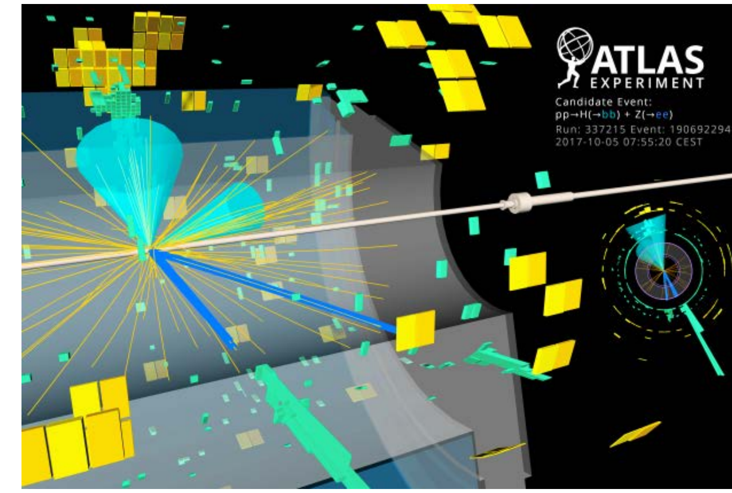
REACHING THE NEXT LEVEL OF PRECISION

Toward a complete theory of non-global LHC processes

- Based on a powerful new factorization theorem
- Analytic all-order resummation of superleading logarithms for arbitrary jet processes
- Calculation of subleading effects using analytical, numerical and Monte Carlo tools
- *Ab initio* understanding of violations of "conventional" factorization and derivation of generalized factorization theorems



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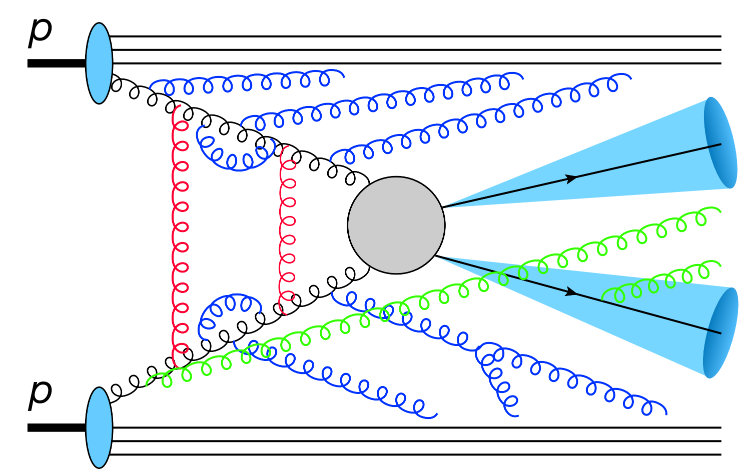

$\Downarrow$

High-precision probes of known and yet unknown phenomena at the energy frontier!